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AN EVALUATION OF LARGE-SCALE PHOTO PLOTS FOR CONDUCTING A FOREST INVENTORY IN YUKON

by

© DAVID J. MORGAN

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

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Abstract

Forest managers in Yukon need to know the most efficient means of obtaining the information required for controlling the Territory's forest resources. This study evaluated the feasibility of substituting for traditional ground-measured plots large-scale photo plots obtained on and measured with systems developed by two different sections of the Canadian Forestry Service. Also compared were measurement accuracies obtained on different types of imagery and by three photogrammetrists on the same imagery.

Analysis of the results indicated that tree height, tree volume and plot area measurements made with the Forest Management Institute and the Northern Forest Research Centre systems did not differ significantly from each other nor from ground measurements of the same variables. Twice-enlarged prints[1] are recommended over other types of imagery tested as such prints yielded the best combination of tree height and plot area measurement accuracy. The results also showed that tree heights could be measured with higher accuracy on black-and-white than on colour prints. Finally, the analysis of tree height measurements made with a Stereocord by three photogrammetrists determined that measurement accuracies did not differ between the three.

This study showed that large-scale photo plots can provide an acceptable and potentially more economical

---

[1] A list of selected definitions of words used in this thesis is provided in appendix I.

alternative to traditional ground-measured plots. The results thus provide guidance to forest resource managers in the Yukon who are faced with determining how to provide needed inventory information within budgetary constraints imposed by the Yukon scene.

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1. Introduction

A little known forest resource is distributed across the Yukon, a Territory of 536,325 km², eighty-one percent of the size of Alberta. The cost of applying traditional forest survey techniques to such northern lands is difficult to justify because the forest productivity is often low, access sometimes difficult, logging operations often costly and markets distant. Development of a cost-effective inventory system appropriate to Yukon conditions and capable of providing land managers with the information needed to enable rational use of forest lands is a basic problem.

Newly developed multistage remote sensing technology appears to offer the most economical solution to this problem (Langley, Aldrich and Heller 1969; Langley 1971; Kirby and van Eck 1977; Kalensky, Moore, Campbell, Wilson and Scott 1981). Landsat imagery can be utilized to rapidly separate forest from nonforest lands including an initial identification of areas likely to contain timber capable of supporting harvesting operations. Medium-scale aerial photography of such lands enables photointerpreters to stratify them into stands which reflect the needs of the forest manager.

Descriptive information on the type, occurrence and condition of the timber in each delineated stand has traditionally been acquired from ground measurements of trees in plots placed at preselected locations. Such plots have become increasingly expensive, particularly in areas

remote from roads. In a 1981 Yukon forest survey conducted by the author costs exceeded $200 per plot even though many of the plot locations were accessible by ground transportation. Nielsen, Aldred and MacLeod (1979) reported that the variable cost of large-scale photo (LSP) plots in a Yukon inventory was $22.25 each, a substantial cost reduction from traditional techniques. The key to the success of such an approach is the determination of the most economical large-scale photo system which will meet inventory objectives.

The problem of photo scale determination had to be solved before LSP systems could be applied operationally to forest inventories. Two fundamentally different solutions have been developed by Canadian researchers. The first, developed by Lyons (1961, 1964, 1966 and 1967), was a tubular boom (with paired cameras mounted one at each end) which could be suspended beneath a helicopter. The system produced stereopairs of photographs by simultaneously triggering the two cameras. Scales equal to the ratio between the photographic air base and the fixed separation of the two cameras were produced, eliminating the problem of scale determination.

The British Columbia Forest Service adopted Lyons' system using twin Hasselblad Mk 70 (70 mm) cameras mounted one at each end of a 6.1 m boom which attaches longitudinally beneath a Bell 206B helicopter (Bradatch 1978).

An alternative Canadian solution to Lyons' design is the use of single, rapid-cycling, rapid-shutter-speed, 70

mm-format cameras mounted on small helicopters or light aircraft. Two such systems have been developed within the Canadian Forestry Service (CFS). An evaluation of the accuracy of the results each system would likely achieve in a Yukon inventory situation is the subject of this thesis.

When selecting an LSP system, factors other than the camera system itself must be evaluated. Various researchers have advocated the use of different imagery including black-and-white, colour and colour infrared films, separately or in combination. Similar disagreement exists regarding the choice of image scale and whether one should use photo positives, negatives or prints for plot measurement purposes. Most researchers and inventory specialists have chosen transparencies for maximum detail or twice-enlarged prints for improved precision.

In addition to the above factors, the determination of individual tree volumes on photographs may be made using different regression equations. Differences in measurement accuracy between individual photogrammetrists is another problem mentioned by many researchers.

The scope of this study was defined by the need to ascertain which combination of equipment, image medium and equation would be best able to meet the informational requirements of a Yukon inventory program. Recommendations arising from the study resulted from addressing five key questions:

1. Is there a difference in the accuracy of individual tree height and plot area estimates using the FMI and NFRC photo measurement systems?

2. Is there a difference in the accuracy of individual tree volume estimates between FMI and NFRC volume equations?

3. Is the accuracy of measurement of tree characteristics related to the image medium?

4. Is colour or black-and-white imagery the more accurate medium for tree measurement?

5. Is there a difference in the accuracy of estimation of individual tree heights on LSP imagery between different photogrammetrists?

Each of the questions is dealt with in separate chapters of this thesis since each question was approached using different procedures and data. A concluding chapter integrates the results of addressing each of these questions and makes recommendations for implementing an operational LSP system in the Yukon.

2. Canadian Forestry Service Equipment Systems

Two LSP data acquisition systems have been developed within the Canadian Forestry Service, one at the Northern Forest Research Centre (NFRC) in Edmonton and the other by staff of the former Forest Management Institute (FMI) in Ottawa with help from the National Research Council. Both systems have been used on large pilot projects although neither system appears ready for operational use without further refinements (Kirby 1979, Aldred 1979).

2.0.1 The FMI System

The details of the FMI system are well documented in Brun (1972), Nielsen (1974a), Aldred (1975) and Aldred and Lowe (1978). The main components of the system are a Westby radar altimeter, a tilt indicator, an intervalometer and one or two Vinten 70 mm cameras. The radar altimeter and the tilt indicator are unique to the FMI system.

The radar altimeter records camera height above the ground with inaccuracies of less than one percent over level terrain for the altitude range of 240-1000 m. The radar was designed to penetrate through the vegetation canopy. The absolute error of the altimeter increases to six meters over irregular terrain. The unit provides a continuous trace of the aircraft-to-ground distance on a strip chart and also

can record each triggering of the cameras. A secondary optics system prints the aircraft height digitally on each photograph.

Nielsen (1974a) reported that steep slopes and aircraft tilt in excess of seven degrees could introduce significant error in height measurement. Moreover, the mechanism requires a few seconds to stabilize following a marked change in aircraft attitude. Nielsen, Aldred and MacLeod (1979) reported an error of less than one percent in a 1977 project in the Yukon.

Research by Johnson (1962), Schut and van Wijk (1965), Brun (1972) and Aldred (1971) indicated that tilt is one of the main sources of error in the photogrammetric determination of tree height. The tilt problem is accentuated when large-scale, small-format photography is used (Nielsen 1974b). To rectify this problem the FMI staff sponsored the development of an airborne tilt-indicator that measures angles of longitudinal and lateral tilt. Readings are recorded through a system of secondary optics on each photograph as a series of binary dots making analytical corrections of tilt possible. During a 1977 inventory project in the Yukon, tests over calm water showed that tilt readings were within 0.2 degrees of correct tilt sixty-five percent of the time and that the error never exceeded 0.4 degrees (Nielsen *et al.* 1979).

2.0.2 The NFRC System

The NFRC system was described in considerable detail by Kirby (1980). The hardware essentially consists of two 70 mm Vinten cameras, an intervalometer and a Honeywell radar altimeter. Through secondary optics camera height above ground and flight time are recorded digitally on each photograph. Kirby and Hall (1981) tested the altimeter and found that its accuracy varied with flying height; for the altitude range 45-600 m the error was 1.6-2.3%, comparable to the FMI unit. A trial of the system in the Yukon yielded inaccuracies of less than 2.3%. NFRC staff claim to have experienced few problems due to tilt (Kirby 1979) perhaps due to avoidance of unstable air during photo missions (Kirby and Johnstone (1970) obtained the photographs required for their project between 0930 and 1030 hours) and through the use of faster camera shutter speeds and film cycling rates that permit the photo plane to fly at faster air speeds and hence in a more stable fashion.

Tilt compensation capability is the factor which separates the two systems. Brun (1972) considered unacceptable any stereopair of photos showing a difference in base lengths (principal to conjugate principal point distances) in excess of five percent. He calculated that such a degree of tilt could produce a five percent error in tree height estimates and nearly twice that in crown area estimates. Kirby (1979) agreed that not using such photos would be the best method of taking tilt into account with

his equipment. He felt that the number of such discards would be less than twenty percent.

Both the FMI and the NFRC systems utilize a stereoscope/digitizer/microcomputer combination for analyzing their respective LSP imagery. The FMI-developed system (called a Stereocord) is now marketed commercially by Zeiss (Aldred and Lowe 1978). The NFRC system consists of a Jena Interpretoskop interfaced with a digitizer, a printer/plotter and the same microcomputer used in the Stereocord.

2.1 Problem Outline

Which of these two systems is best suited to Yukon conditions? Idealy a trial of the two comparing their ability to measure the same tree heights and plot areas would be needed to answer this question. Because suitable Yukon imagery could not be obtained, photography taken in Alberta in 1978 with the FMI camera system was used in this test. As the NFRC system does not take aircraft attitude into account, it was assumed that the same imagery could be used to simulate that which NFRC equipment would have produced simply by ignoring the positioning information.

Tree diameters and volumes on large-scale vertical aerial photographs are typically estimated by their relationship to variables which can be measured directly on the photos. Tree height, normally measured by the differential parallax method (Thompson 1966, Wolf 1974), is the

most useful such variable. Kirby and van Eck (1977) obtained coefficients of determination (r^2) of 0.79 and 0.59 for gross volume with tree height for white spruce and aspen, respectively, in northern Alberta. Height is the only variable used by NFRC staff to estimate individual tree volumes on large-scale photo plots (Kirby 1979). Tree lean is normally ignored as lean must exceed 11.5 degrees before height is affected more than two percent (Aldred and Sayn-Wittgenstein 1972). Since tree height is the primary variable used for volume estimation on large-scale aerial photos, the performance of the two systems was compared by evaluating the accuracy with which each could estimate individual tree height.

Forest inventory normally involves sampling the forest on the basis of a discrete unit, often a plot of fixed size (or assumed so for the purposes of calculation). Data obtained from each unit or groups of units are later multiplied by some factor to expand the estimate to cover the full area surveyed. The resulting expansion of the plot measurements may introduce an error of considerable magnitude into the final volume estimation. Confirming that the photo plot areas were correct was an important part of this study.

2.2 Experimental Methods

2.2.1 Hypothesis and Tests

A comparison of the two LSP systems was made by testing the following hypothesis:

> The FMI and NFRC large-scale photo systems yield estimates of equal accuracy for individual tree heights and plot areas.

This test involved three photogrammetrists using a Stereocord and a fourth employing an Interpretoskop to measure 127 individual heights in 12 LSP plots. While more trees were contained within the plots, only those trees measured for height by all four photogrammetrists were used in the comparison. The accuracy of measurement was assessed by comparing the photo-estimated heights with measurements of the same trees felled (the dependent variable) using a two-way anova at the five percent level of significance. The effect on the accuracy of measurement of the five different species of trees involved was the second factor appraised.

To assess the accuracy with which the Stereocord and the Interpretoskop can be used to estimate plot area, the twelve plots were measured for area by two photogrammetrists, one using each of the measuring devices tested. Plot areas were also ascertained by a ground survey. A randomized complete block anova at the five percent level was employed to compare the three independent area measurements by treating each plot as a block. This approach reduced the experimental error by removing between-block

variation and thus showed more clearly measurement differences (Mendenhall 1979). Because only twelve plot area measurements were available, nonparametric tests (the Wilcoxon signed rank and the Siegel-Tukey) were also applied to the data to check the anova result.

2.2.2 Test Sites

As imagery suitable for testing the hypothesis was not available from the Yukon, pre-existing Alberta Forest Service photography of an area in west central Alberta (figure 1) with terrain and vegetation similar to that typically found in the Yukon was chosen for this trial. Rowe (1972) classified that forest as B.18 within his Boreal Forest Section. He described the test area as, "the characteristic vegetation of the well-drained uplands is a mixture in varying proportions of trembling aspen and balsam poplar, white and Alaska birches, white spruce and balsam fir, the latter two species being especially prominant in old stands".

The FMI camera equipment, loaded with Kodak double-X aerographic 2405 (black-and-white negative) film, was mounted on a Helio-Courier STOL aircraft and used during May of 1978 to obtain randomly-located flight transects. The negatives had a nominal scale of 1:1000 and were used to produce twice-enlarged prints as recommended by Brun (1972). From amongst those prints twenty stereopairs were chosen for photo plot establishment based largely on ease of access.

Boundaries were placed so that each plot contained approximately 70 trees. Plot areas (on the ground) ranged from 80 to 700 m^2 depending on tree density. The plots contained various mixtures of tree species including white spruce (*Picea glauca (Moench) Voss*), black spruce (*Picea mariana (Mill.) B.S.P.*), lodgepole pine (*Pinus contorta Dougl.*), trembling aspen (*Populus tremuloides Michx.*), and balsam poplar (*Populus balsamifera L.*).

2.2.3 Measurement Procedures

After plot boundaries had been defined on the stereopairs, all trees visible on the photos in each plot were numbered. Individual tree species, height and crown area, and plot area, were recorded for most photo plots by three AFS photogrammetrists on a Stereocord. Neither every tree nor every plot boundary was measured by every photogrammetrist because the test was originally intended primarily as a staff training exercise rather than a scientific trial of the system. Independently the plot trees were measured on site for total height and diameter at breast height. Height measurements were made on standing and/or felled trees. Plot boundaries were also measured on the ground. A fourth photogrammetrist independently measured the tree heights and plot areas on the photos at a later date using the NFRC Interpretoskop to permit a comparison of the instrument's performance to that of the Stereocord.

Figure 1: Location of AFS plots in Alberta

This procedure resulted in measurements which were not duplicated by each photogrammetrist. Using all of the trees measured by one or more persons would have required a sophistication beyond that which was practical with the tools available. Therefore, in order to simplify the statistical comparisons, the author chose to use only those trees which were measured by all four interpreters and by ground crews (127 in 12 plots). For the selected trees, "ground" heights were a mixture of felled and standing height measurements, all of which were converted to "felled" heights through use of a simple linear regression (appendix II).

As few plot area measurements from the AFS photogrammetrists were available, the author chose to use only those of the AFS photogrammetrist for whom the largest number of plot areas were duplicated by ground-measured areas for comparison with the area measurements made with the NFRC Interpretoskop.

2.3 Results

Individual tree heights measured on the ground were not significantly different at the five percent level from those measured on the large-scale photos with the Stereocord or with the Interpretoskop (table 1). This accuracy of measurement extended even to the hardwoods which had yet to flush at the time the aerial photography was taken. Tree

Table 1. Two-way anova[1] assessing effects of measurement system[2] and species differences on accuracy of tree height[3] estimation on twice-enlarged prints

Anova Table

Variation Source	df	SS	MS	F	Critical F
Main Effects					
Species	4	4,653.51	1163.38	68.34	2.37
Systems	4	34.04	8.51	0.50	2.37
Interaction					
Spec./Syst.	16	94.91	5.93	0.35	1.65
Residual	610	10,383.97	17.02		
Total	634	15,166.43			

[1]Analysis of variance 5% level of significance
[2]3 interpreters using a Stereocord and 1 using an Interpretoskop measured the tree heights
[3]127 trees of 5 species in 12 plots

Statistical Comparison of Tree Heights[1]

Height Source	Mean Height	Standard Deviation	Standard Error
Standing/Felled	16.3119	4.8440	0.4298
NFRC	16.3582	4.9707	0.4411
FMI 1	16.4023	5.1242	0.4547
2	15.9157	4.8543	0.4307
3	16.3061	3.7022	0.4173

[1]Total tree height in meters

Table 2. Randomized complete block anova[1] comparing areas (m^2) of 12 LSP plots measured on the ground and on twice-enlarged prints[1]

Anova Table					
Variation Source	df	SS	MS	F	Critical F
Plots	11	1,033,101.9	93,918.4	386.5	2.26
Measurements	2	829.3	414.6	1.7	3.44
Error	22	5,345.5	243.0		
Total	35	1,039,276.7			

[1]Analysis of variance 5% level of significance
[2]Two interpreters using FMI and NFRC equipment made the measurements

Table 3. Statistical evaluation of the accuracy with which two LSP measurement methods[1] can determine plot area

Measurement Instrument	Significance at .05 Level of Differences Between Ground and Photo Area Measurements		
	Siegel-Tukey Test	Wilcoxon Signed Ranks Test	Paired T Test
Stereocord	not significant	significant	not significant
Interpretoskop	not significant	not significant	not significant

[1]12 plots measured by 2 photogrammetrists, one using an Interpretoskop and the other a Stereocord

Statistical comparison of 12 area measurements(m^2)

Statistic	Ground	FMI	NFRC
Mean Area	248.208	258.275	258.501
St'd Dev.	181.726	169.793	180.417

heights did vary significantly with tree species.

Results of the anova, Siegel-Tukey and paired t tests comparing photo-measured to ground-measured plot areas indicated that the differences were not significant at the five percent level (table 2). When the Wilcoxon signed ranks test was applied, however, the Stereocord-measured plot areas were found to differ significantly from ground measurements ($p = .042$) whereas the Interpretoskop-measured plot areas were accepted ($p = .062$).

2.4 Discussion

In retrospect, this test could have been improved had the trial been planned as a scientific comparison of the two systems from the beginning. As in most studies, certain assumptions had to be made like the equivalency of the FMI prints to those which would have been produced with NFRC equipment under similar flight conditions. The comparison did indicate that either LSP system can provide comparable estimates of tree height and plot area to ground measurements.

Theoretical calculations by researchers like Brun (1972) have emphasized the magnitude of the errors which may result from ignoring tilt. While reducing the time interval between sequential exposures may minimize tilt effects, further study of the subject would be desirable to gain a knowledge of the magnitude of error likely to result from

ignoring tilt during normal LSP operations. A definition of the accuracy needs of forest managers and the funds likely to be available for overcoming tilt errors would also be desirable before further studies of this topic are undertaken.

Since the terrain and forest types present throughout much of the Yukon's potentially commercial forest zone are similar to those encountered during the Alberta test, the results of this study revealed that in a Yukon inventory ground plots or those produced by either LSP system could be employed depending upon the economics of the situation.

3. Regression Equations

NFRC and FMI staff have chosen to use different regression equations to estimate individual tree volumes. NFRC staff use a quadratic equation of the form:

$$V = a + bH + cH^2$$

where V = volume in m^3

H = total tree height in metres, and

a, b, c = estimates of coefficients calculated using multiple linear regression techniques.

FMI staff advocate an equation having exponential regression coefficients with a logarithmic transformation to the linear form:

$$\log V = a + b \log CA + c \log H$$

where V = volume in m^3

CA = crown area in m^2

a, b, c = estimates of coefficients calculated using multiple linear regression techniques.

Researchers agree (Aldred and Sayn-Wittgenstein 1972) that tree height alone has a very strong correlation with volume. Crown width or crown area is also commonly used for estimating tree diameters or volumes but seldom alone, as the relationship between crown size and tree diameter is too weak. Such crown measurements need not conform to ground measurements but do need to be precisely reproducible (Aldred and Sayn-Wittgenstein 1972). Kirby and Johnstone (1970) found that for lodgepole pine in western Alberta the addition of photo-measured crown width with tree height to a

regression for predicting individual tree diameter and volume significantly improved the estimations. White spruce did not exhibit the same strong relationship between volume and crown diameter. Bonnor (1964, 1968) found that photo measurements of height and visible crown diameter provided good estimates of stem diameter for six conifers and five hardwoods. Johnstone (1976) and others found that "many of the growth expressions of lodgepole pine (including volume, average stand height, average diameter and dominant height) are strongly influenced by stand density regardless of physiographic site".

Crown area has also been used with tree height to determine tree volume. Aldred and Sayn-Wittgenstein (1972) found that crown area was superior to crown width due to the difficulty of obtaining consistent measures of the latter. Brun (1972) also found crown diameter measurements too inconsistent to be useful. Aldred (1979), using data collected by the Alberta Forest Service, obtained strong correlations between white spruce volume and tree height. The standard error of estimate (although not the correlations) improved considerably when crown area was added to the regression. He also stated that although the correlations of tree height with volume for hardwoods and lodgepole pine were not as strong, the addition of crown area to the regressions still markedly reduced the standard error of estimation.

3.1 Problem Outline

Which regression should be used for Yukon inventory purposes? Tests conducted by Yukon Forest Resources staff on the AFS Stereocord revealed that the addition of crown area measurements to the other necessary photo plot measurements doubled the measurement time per plot. Crown area must therefore contribute substantially to the accuracy of volume estimation over the use of tree height alone before the addition of crown area to the regression is worthwhile.

3.2 Experimental Methods

3.2.1 Hypothesis and Tests

In order to address this problem, the following hypothesis was formulated:

> The FMI regression equation (based on crown area and height) is no more accurate for estimating individual tree volumes than the NFRC regression equation (based on height alone).

The accuracy with which individual tree volumes can be estimated using the FMI and the NFRC regression equations was assessed by comparing the photo-estimated volumes with independently-obtained ground measurements (standing and felled) of the same trees. This assessment utilized a randomized complete block anova at the five percent level of significance with each of the trees being treated as a randomly chosen block. The felled volumes were considered to be accurate measurements to which were compared the other

three estimates, one at a time.

3.2.2 Test Sites

A test site (site 1, figure 2) along the South Canol Road was selected because the timber was representative of much of the potentially commercial Yukon forest. The location was situated in the Boreal Forest Section classified by Rowe (1972) as B.26b. He describes the valley situation as, "on water-modified tills and coarse terrace materials, lodgepole pine and white spruce share dominance in closed or open but rarely tall stands. Trembling aspen is a frequent associate of the conifers, and the mixed spruce-pine-aspen type is common...".

The black-and-white imagery used to address this hypothesis was obtained in August 1979 under adverse weather conditions (between rain squalls) using NFRC equipment mounted inside a deHavilland DHC-6 twin otter aircraft. Approximately 450 frames (one magazine) of Kodak double-X aerographic 2405 (black-and-white) film were exposed in a strip paralleling the South Canol Road (site 1, figure 2) north of Teslin. This film was processed to produce contact-scale, two-times- and four-times-enlarged prints and contact-scale positive and negative transparencies. In order to avoid possible "patterning" in the growth of the timber, the eleven plot locations used in this test were chosen at random from the available stereopairs (three sites for each scale of print and two for each type of transparency). Where

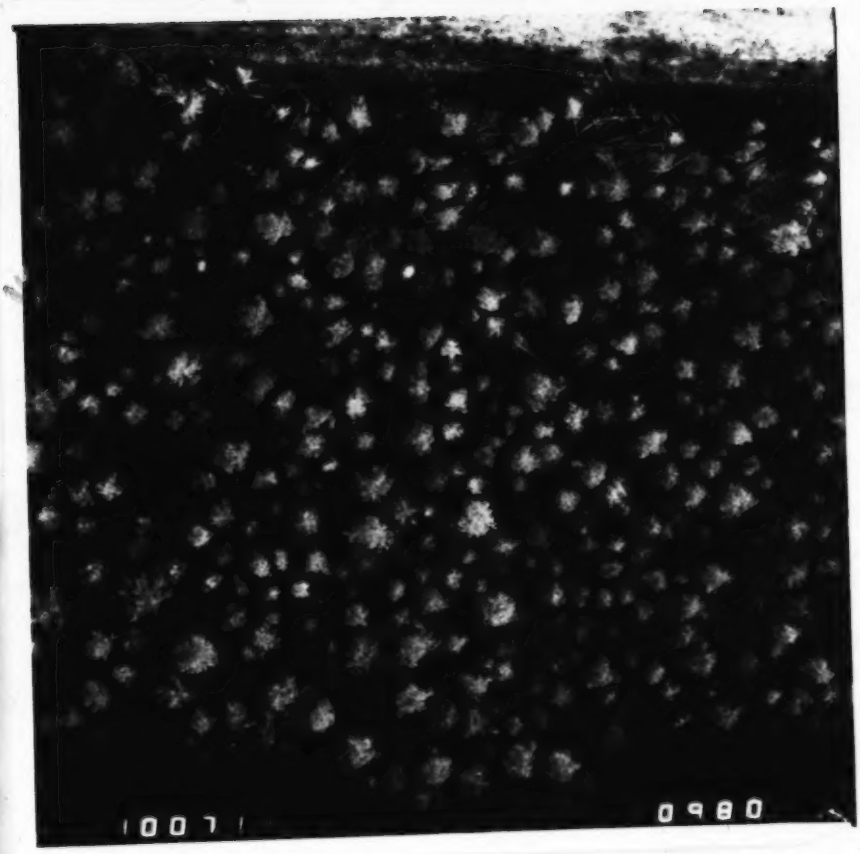

Figure 2: Twice-enlarged print from the South Canol Road area (site 1, figure 2). The aircraft height and the flight time at the moment of exposure are recorded at the bottom of the photograph.

the sites selected had a crown closure of less than ten percent (classified as nonforest by Yukon foresters) new plot locations were randomly chosen.

3.2.3 Measurement Procedures

Plot boundaries were located on the applicable photographs using a templet designed to yield square plots (on level ground) with boundaries of 17.4 m on a side. Templet dimensions were calculated by using an average of the radar altimeter readings for the entire film "strip" rather than by calculating plot sizes photo by photo.

Individual tree heights were measured by one photogrammetrist using a Jena Interpretoskop. Individual tree crown diameters were measured with a plastic scale in two directions at right angles to each other then arithmetically averaged. This approach, also used by Kirby and Johnstone (1970), assumes that tree crowns are circular rather than elliptical. Crown areas were calculated using the formula for the area of a circle. The assumption was made that this technique, required by equipment limitations, would result in values approximating those which would be generated by measuring the same crowns on a Stereocord.

Field truthing of the photo measurements by an independent crew was accomplished by locating (with the aid of the photos) and measuring the plot boundaries on the ground. Individual trees in the plots were numbered as on the photographs, and their species, diameters at breast

height and total standing height (to the nearest 0.1 m) recorded. Later a second crew felled and measured the total heights of all of the trees in the eleven plots.

Individual tree volumes were obtained by using the felled tree dimensions and an individual tree volume equation prepared by University of Alberta staff from 920 felled and measured lodgepole pine from sites throughout south central Yukon. This procedure was assumed to provide accurate estimates of tree volume.

The NFRC and FMI equation coefficients were generated by regressing the tree volumes of 349 trees from 11 plots with photo-measured tree height or log tree height and log crown area, respectively, using multiple linear regression techniques.

Since equipment differences had already been assessed by testing hypothesis 1, the same tree height measurements were used in both equations in this comparison. Aircraft attitude at the time of photo exposure was ignored as the NFRC system does not record such data.

3.3 Results

A multiple linear regression analysis of the data yielded the following equations:

NFRC: $V = 0.3125374 - 0.04598170\ H + 0.002157587\ H^2$

with $r^2 = 0.7058$ and standard error = $0.03112\ m^3$

FMI: $\log V = -3.534243 + 0.1409680\ \log CA + 2.177128\ \log H$

with $r^2 = 0.7761$ and standard error = 0.03116 m^3

The randomized complete block anova comparison showed that felled volumes did not differ significantly from the 'standing', NFRC or FMI volume estimations at the ninety-five percent level of confidence as illustrated in tables 4, 5 and 6, respectively. Summary statistics comparing tree volumes produced by each of the four measurement systems are shown in table 7.

An F test as described by Snedecor and Cochran (1967) comparing the variances of volumes produced by the two equations showed that those variances did not differ significantly at the ninety-five percent level of confidence. The usual F tests were also performed on the equation coefficients. All proved to be significant at the five percent level.

3.4 Discussion

The results of this test indicate that individual tree volume can be estimated as accurately using photo tree height alone (the NFRC approach) as by using log photo tree height and log crown area (the FMI approach). The Table 7 figures illustrate the the similarity of the outcomes obtained from the four measurement systems. These results should be applied with caution, however, since the study involved only one tree species (lodgepole pine) growing in a very restricted area.

Table 4. Randomized complete block anova[1] comparing felled to standing volume[2] estimations(m^3)

Anova Table					
Source of Variation	df	SS	MS	F	Critical F
Measurement System	1	0.00001	0.00001	0.36	3.84
Individual Trees	348	2.33052	0.00670	167.50	1.14
Remainder	348	0.01273	0.00004		
Total	697	2.34326			

[1]Analysis of variance 5% level of significance
[2]349 trees from 11 plots

Table 5. Randomized complete block anova[1] comparing felled to NFRC equation volumes[2]

Anova Table					
Source of Variation	df	SS	MS	F	Critical F
Measurement System	1	0.0003	0.0003	0.57	3.84
Individual Trees	348	1.7754	0.0051	10.63	1.14
Remainder	348	0.1677	0.0005		
Total	697	1.9434			

[1]Analysis of variance 5% level of significance
[2]349 trees in 11 plots

Table 6. Randomized complete block anova[1] comparing felled to FMI equation volumes[2]

Anova Table					
Source of Variation	df	SS	MS	F	Critical F
Measurement System	1	0.0014	0.0014	3.44	3.84
Individual Trees	348	1.6859	0.0048	11.82	1.14
Remainder	348	0.1431	0.0004		
Total	697	1.8304			

[1]Analysis of variance 5% level of significance
[2]349 trees in 11 plots

Table 7. Comparative statistics (m^3) for four measurement systems

Measurement System	Total Volume	Average Volume	Standard Deviation
Felled	47.44446	0.13594	0.057210
Standing	47.35000	0.13569	0.058840
NFRC	47.44446	0.13594	0.048064
FMI	46.45330	0.13310	0.044531

[1]349 lodgepole pine trees in 11 plots

This outcome has important connotations for Yukon photo volume estimations since eliminating crown area from photo plot measurements reduces the time necessary to measure each plot by half.

4. Image Scale and Type

A variety of image media has been used for LSP purposes, each having its own set of advantages and disadvantages. Three aspects must be assessed: the photo scale, the image type and the film emulsion. The third aspect will be addressed in a later section of this thesis.

For many forestry purposes, the best scale of photograph to use for various purposes has yet to be determined. Kirby and Johnstone (1970), using four-times-enlarged prints from black-and-white panchromatic negatives for measuring tree heights and crown widths of boreal trees in Alberta, obtained equally acceptable results using original negative scales of 1:2400 and of 1:1200. Brun (1972) recommended two-times enlargements of black-and-white panchromatic 1:1500 negatives for easiest recognition of crown area and tree heights in Ontario. Scales larger than 1:1000 posed operational difficulties; the exaggerated parallax causes discomfort to the interpreters. Bonnor (1977), after finding that a film scale of 1:2100 was too small for effective tree height and crown separation, suggested a film scale of 1:1000. Ashley, Rae and Wright (1976) found that CIR transparencies at a scale of 1:9,900 or larger enabled consistent recognition of individual tree mortality. Heller, Doverspike and Aldrich (1964) recommended colour photography at a scale of 1:1584 or larger for species identification. Thus the choice of 70 mm photo scale seemingly depends upon the stand density, the tree species, the locality and the

objective of the project.

A film scale of approximately 1:1000 has now been accepted by most Canadian users for LSP applications. This scale should provide adequate detail at acceptable cost in most situations. Aircraft behavior has also had a bearing on this decision. Most aircraft should not be operated below certain elevations for safety reasons. Also, the air close to the ground is often more turbulent, affecting image quality.

After the initial film scale has been chosen, the scale of the final image can still be altered by enlargement. Brun (1972) found that tree details on two-times-enlarged prints of 1:1000 70 mm black-and-white negatives could be clearly observed. Further enlargement reduced image quality due to resolution limitations, image motion, and other factors. Allison (1956) discovered that measurements for tree height estimation on 1.85 enlargements were more accurate than others made on 2.8 enlargements. Lee (1959) and Smith, Lee and Dobie (1960) found no significant advantage to the use of transparencies versus prints. Anson (1959) during a stereo acuity study discovered that transparencies were 9.7-12.8% better than paper prints. Studies by Welsh (1968) have shown that as much detail can be seen on a contact-scale transparency as upon a five-times-enlarged paper print because the definition of objects near the threshold of detection is much higher with positive transparencies. Wolf (1974) recommended positive transparencies for interpre-

Figure 3. NFRC camera system consisting of a Honeywell radar altimeter mounted between two Vinten cameras under a Bell 206B helicopter.

tation due to increased detail and the excellent stability of film versus paper prints. Oswald (1978), Dempster (1978), Bradatch (1978) and others who have made operational use of aerial photographs for vegetation analysis also recommend transparencies for office interpretation where equipment is available to enlarge the imagery to whatever degree is desired. Prints are recommended for field use as the transparencies scratch easily. Ashley *et al.* (1976) found that details of tree crowns could best be seen on backlit CIR transparencies. Bradatch (1978) stated that colour positives provide superior interpretation results. Thus researchers have switched from paper prints to transparencies in recent years. The change may be partially attributable to the development in the 1960's of new films with finer grain and increased sensitivity (Driscoll 1974). Which LSP image media is the best suited for Yukon forest inventory applications?

4.1 Problem Outline

Most researchers agree that for general inventory purposes (i.e., volume estimation) an LSP film scale of 1:1000 is desirable. Wide disagreement exists, however, regarding the scale and type of imagery that should be used for the actual tree measurements. Given that a Jena Interpretoskop will be used for LSP measurement purposes in

the Yukon, should 1:1000 imagery (negatives, positives or prints) or two- or four-times enlargements be employed for LSP plot measurement?

4.2 Experimental Methods

4.2.1 Hypothesis and Tests

The choice of the best image type can best be decided by testing the following hypothesis:

> Measurements of tree height and plot area on 1:1000 LSP imagery can be made with equal accuracy on black-and-white contact-scale, twice- and four-times-enlarged prints and contact-scale transparencies (positive and negative).

The accuracy with which tree height and hence volume can be estimated on various types of imagery was evaluated by comparing individual tree height estimates to ground-measured values. The same statistical method (a randomized complete block anova at the five percent level of significance, with individual trees treated as blocks) was used. This design is possible because the same trees were measured on the ground and on the photos. The imagery which provided results closest to the ground-measured values was deemed the most accurate.

Tree heights measured on each type of imagery were compared with height measurements made on the ground independently from measurements made on other types of imagery. This procedure was used rather than a group

comparison because all calculations had to be done by hand. The number of trees in each sample also varied greatly.

Plot areas measured on the ground and on four of the five types of imagery were also compared to ground values using nonparametric tests due to the small number of samples available (an average of six plots per image type).

4.2.2 Test Sites

Site 1 (figure 2) along the South Canol Road in the Yukon was also chosen for this portion of the study. A description of the location can be found in section 3.2.2.

The same photography used to test the regression equations was utilized for this trial. From the site 1 photography (a strip of 450 photos) twenty-eight plots were selected at random. These included 18 plots on prints (6 plots each on contact-scale, 1.98- and 4.28-enlarged prints) and 10 plots on transparencies (6 on negatives and 4 on positives). The 11 plots utilized in the comparison of the regression equations were also included in this test.

As in the previous section, the plots were located on the photos using a templet designed to provide square plots on level ground 17.4 m on a side (using a photo scale based on an average of the radar altimeter readings for the whole strip).

4.2.3 Measurement Procedures

The individual trees were measured on the ground (standing, with tape and clinometer) as well as independently with an Interpretoskop on the appropriate LSP stereopairs. All the trees in at least two plots for each type of imagery were also felled and measured. The boundaries of the twenty-two plots were surveyed with staff compass and chain. Due to time limitations the boundaries of the four plots selected on the positive transparencies could not be measured on the ground.

4.3 Results

Tables 8 to 19 show the results of this series of tests. Tree heights measured on the negative transparencies, the twice-enlarged prints and the contact prints were equal in accuracy to the standing-measured tree heights (as shown by the coefficients of determination (r^2) and the standard errors listed in tables 15, 11, and 13, respectively). Only tree heights measured on the four-times-enlarged prints (table 8) did not differ significantly at the five percent level from standing measurements of the same trees. Table 18 lists the results obtained through pooling of all photo tree height measurements and their associated felled and standing measurements. Those done on the standing trees were more closely correlated to the felled heights than measurements made on the photographs.

Table 8. Randomized complete block anova[1] comparing tree heights measured on the ground[2] with estimates made on four-times-enlarged prints[3]

Anova Table

Source of Variation	df	SS	MS	F	Critical F
Measurement Method	1	2.34	2.34	1.59	3.84
Individual Trees	226	3,120.57	13.75	9.35	1.16
Remainder	226	332.12	1.47		
Total	435	3,455.03			

[1]Analysis of variance 5% level of significance
[2]Lodgepole pine heights measured standing
[3]227 trees in 6 LSP plots South Canol Road

Table 9. Statistical comparison of lodgepole pine heights[1] measured on the ground[2] and on four-times-enlarged black-and-white prints

Measurement System	Mean Height	Standard Deviation	Felled r^2	Felled SE E	Standing SE E
Photo	15.5124	2.05247	0.68356	1.20089	1.15122
Standing	15.2981	2.18922	0.89276	0.69911	
Felled	15.3848	2.12453			

[1]105 tree heights (m) in 3 plots along South Canol Road
[2]Measured felled and standing

Table 10. Randomized complete block anova[1] comparing tree heights measured on the ground with photo heights[2] on twice-enlarged prints

Anova Table

Source of Variation	df	SS	MS	F	Critical F
Measurement Method	1	14.59	14.59	21.32	3.84
Individual Trees	242	2,119.00	8.76	12.80	1.16
Remainder	242	165.58	0.68		
Total	485	2,299.17			

[1]Analysis of variance 5% level of significance
[2]243 lodgepole pine in 6 plots South Canol Road

Table 11. Statistical comparison of tree heights[1] measured on the ground[2] and on twice-enlarged prints

Measurement System	Mean Height	Standard Deviation	Felled r^2	Felled SE_E	Felled SE_E
Photo	15.7000	1.9470	0.8016	0.9764	0.9862
Standing	15.3934	2.1687	0.7972	0.9871	
Felled	15.5698	2.1818			

[1]105 trees in 3 plots South Canol Road area
[2]Measured felled and standing

Table 12. Randomized complete block anova[1] comparing tree heights[2] measured on the ground[3] with photo heights on contact prints

Anova Table

Source of Variation	df	SS	MS	F	Critical F
Measurement Methods	1	15.70	15.11	12.61	3.84
Individual Trees	215	2,454.19	11.41	9.52	1.16
Remainder	215	257.69	1.20		
Total	431	2,727.58			

[1]Analysis of variance 5% level of significance
[2]216 lodgepole pine in 6 plots South Canol Road
[3]Standing height

Table 13. Statistical comparison of tree heights measured on the ground[1] and on contact prints

Measurement Method	Mean Height	Standard Deviation	Felled r^2	Felled SE E	Standing SE E
Photo	16.5273	2.18566	0.85094	1.15212	1.58644
Standing	16.8455	3.40517	0.87867	1.06889	
Felled	16.7545	3.05298			

[1]99 tree heights (in metres) from 3 plots South Canol Road

Table 14. Randomized complete block anova[1] comparing standing to photo heights[2] on negatives

Anova Table					
Source of Variation	df	SS	MS	F	Critical F
Measurement Methods	1	21.04	21.04	22.87	3.84
Individual Trees	162	1,632.71	10.08	10.95	1.18
Remainder	162	149.07	0.93		
Total	325	1,802.82			

[1]Analysis of variance 5% level of significance
[2]163 lodgepole pine in six plots, South Canol Road

Table 15. Statistical comparison of tree heights[1] measured on the ground[2] and on negative transparencies

Measurement Method	Mean Height	Standard Deviation	Felled r^2	Felled SE E	Standing SE E
Photo	15.0468	1.7652	0.80138	0.9085	0.91677
Standing	14.8694	1.9875	0.80987	0.90096	
Felled	15.0887	2.0492			

[1]62 lodgepole pine heights (m) in 3 plots South Canol Road
[2]Felled and standing

Table 16. Randomized complete block anova[1] comparing tree heights[2] measured standing and on positive transparencies

Source of Variation	df	SS	MS	F	Critical F
Measurement Method	1	9.23	9.23	8.30	3.84
Individual Trees	175	1,100.81	6.29	5.66	1.18
Remainder	175	194.53	1.11		
Total	351	1,304.57			

[1]Analysis of variance 5% level of significance
[2]176 lodgepole pine in 4 plots South Canol Road

Table 17. Statistical comparison of tree heights[1] measured on the ground and on positive transparencies

Measurement Method	Mean Height	Standard Deviation	Felled r^2	Felled SE E	Standing SE E
Photo	17.9223	2.14179	0.69244	1.08758	1.54466
Standing	17.3198	2.18413	0.80599	0.86381	
Felled	17.5116	1.95291			

[1]121 lodgepole pine in 3 plots South Canol Road

Table 18. Summary statistical comparison of Lodgepole pine heights measured on the ground and on LSP imagery[1]

Measurement Method	Mean Height	Standard Deviation	Felled r^2	Felled SE E	Standing SE E
Photo	16.2895	2.28509	0.77867	1.16742	1.40880
Standing	16.0716	2.62532	0.86250	0.92016	
Felled	16.1844	2.47894			

[1]493 tree heights(m) in 15 plots South Canol Road area

Table 19. Comparison of Yukon plot area measurements made on the ground with photo estimations

Image Type	No. Plots	Significance of Differences Between Ground and Photo Measurements		
		Siegel-Tukey Test	Wilcoxon Signed Rank Test	Paired T Test
4X B/W Print	6	not significant	not significant	
2X B/W Print	6	not significant	not significant	
Contact B/W Print	6	significant	significant	
B/W Negative	4	significant	significant	
2X Color Print	12	not significant	not significant	not significant
All Imagery	34			not significant

Note: All tests done at the 5% level of significance
B/W means black-and-white
2X, 4X indicates degree of print enlargement
B/W imagery from South Canol Road area
Colour prints from Braeburn Lake area

Only plot areas measured on the two-times- and four-times-enlarged prints (table 19) did not differ significantly at the five percent level from ground-measured plot areas. Nonparametric tests were included in this evaluation due to the small number of plots available for comparison.

4.4 Discussion

The hypothesis was disproved only in regard to the four-times-enlarged prints and the positive transparencies. The accuracy of tree height measurement found in this test was similar to the results obtained by other researchers. Aldred (1979) reported that the standard error of estimate for photo-measured and standing-measured versus felled heights for 600 trees (the total compared from Alberta and Yukon plots) was less for the photo heights (0.7 versus 1.1 m, respectively). Lyons (1966, 1967) reported comparable outcomes.

The twice-enlarged prints provided the best combination of plot area and tree height accuracy, equal to the results one could expect from plots measured on the ground. Yukon foresters could use such photography as the prime stand-sampling medium in a Yukon inventory of the Territory.

5. Film Emulsion

Traditionally foresters have used black-and-white aerial photography for forest inventory purposes. Such imagery depends on differring tones of grey for feature differentiation. Colour photography has given photo-interpreters three new dimensions that black and white photos cannot provide: hue(colour), value, and chroma or strength (Evans 1948). These qualities provide additional information on which to base judgments (Heller *et al.* (1964). The introduction of colour photographs has increased our capabilities for research and the management of natural resources. Most aerial resource surveys in the U.S.A. are now undertaken with colour negative film (Driscoll 1974).

Colour photography, particularly colour infrared (CIR), has proven superior to black-and-white for delineating plant communities in many studies (Driscoll 1970, 1974; Driscoll and Coleman 1974; Driscoll and Francis 1970; Valentine, Lord, Watt and Bedwaney 1971). Other researchers have shown that colour large-scale aerial photography can be used to advantage in tree species identification, timber inventories and forest damage appraisal (Sayn-Wittgenstein 1960, 1962, 1978; Heller, Lowe, Aldrich and Weber 1967; Heller *et al.* 1964; Parry, Cowan and Higginbottam 1969; Langley, Aldritch and Heller 1969; Ashley, Rea and Wright 1976; Oswald 1978; Bradatch 1978). Aldred (1979) suggested that even tree measurements can be done more accurately on colour film.

The use of colour and CIR photography instead of black-and-white is not always advantageous. Brun (1972), Bradatch (1978) and Sayn-Wittgenstein (1978) stated that on CIR imagery shaded portions of tree crowns and the ground contain no recognizable details. Oswald (1978) had difficulty obtaining good quality CIR in the Yukon perhaps due to the low sun-angle in those latitudes. Colour film is more costly than black-and-white and has a narrower exposure range. CIR is even more expensive and demanding in its handling requirements before and after exposure.

5.1 Problem Outline

The 70 mm aerial films most commonly used for LSP projects are marketed by Kodak and include double-X aerographic 2405 (black-and-white negative), aerocolor negative 2445 and aerochrome 2443 (CIR). Which of these films can provide the best results in a Yukon forest inventory?

In an attempt to answer this question a trial of all three film types was arranged in the Yukon. Unfortunately rapidly varying light conditions (a bright sunny day with intense shadows caused by low scattered clouds) made setting shutter openings difficult; the infrared photographs were unusable.

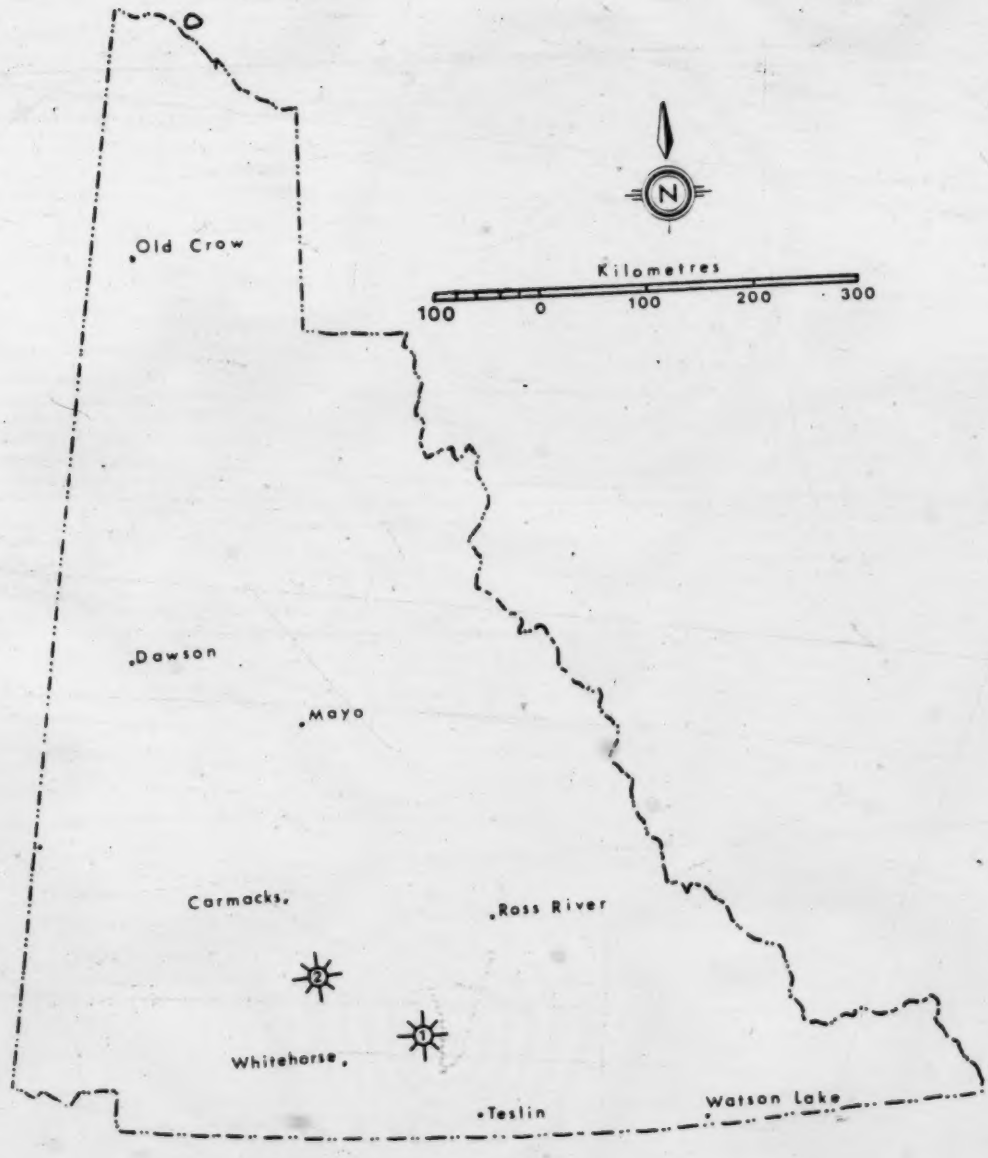

Figure 4: Map showing the Yukon test areas:
(1) South Canol Road, and
(2) Braeburn Lake

5.2 Experimental Methods

5.2.1 Hypothesis and Tests

Addressing this problem requires testing of the following hypothesis:

> Measurement of tree height can be made with equal accuracy on black-and-white and colour twice-enlarged prints.

The colour and black-and-white prints used to test this hypothesis originated from different locations. The assumption was made that because the photo height measurements from both types of prints were tested by comparing them to ground-measured heights of the same trees made by the same crew the tests were equivalent. The assessment utilized a randomized complete block anova at the five percent level with each of the trees being treated as a randomly chosen block.

5.2.2 Test Sites

Two test sites (figure 2) were utilized for this trial due to weather and operational problems. Both locations were situated in the Boreal Forest Section classified by Rowe (1972) as B.26b. His description of the vegetation can be found in section 3.2.2.

The black-and-white twice-enlarged prints used in this comparison were the same ones used in the image type test. A description of the image acquisition procedure can be found in section 3.2.2.

The colour photography was obtained by mounting the NFRC LSP equipment under a Bell 206B helicopter and loading the twin cameras with Kodak aerocolor negative (2445) and aerochrome infrared (2443) film. Five transects (sufficient to use the full camera magazine) were flown south of Braeburn Lake (site 2, figure 2). The 70 mm negatives with a nominal scale of 1:1000 were processed to provide twice-enlarged prints. Along a randomly chosen flight line, twelve photo plots were randomly placed with a minimum distance between plots of 30 m. Plot boundaries were drawn on the prints with a templet designed to provide square plots 15 m on a side (on the ground). Templet dimensions were based on the average photo scale (1:527). The actual photo scale varied within and between plots.

5.2.3 Measurement Procedures

Individual tree heights were measured in each LSP plot by one photogrammetrist using an Interpretoskop. Plot areas were measured on the photos with a metric ruler. Later ground crews flagged and surveyed plot boundaries, and measured the standing height of each plot tree. No trees were felled in these plots to check the accuracy of the ground-measured tree heights.

5.3 Results

Tables 20 to 23 list the results. The randomized complete block anova indicated that photo height measurements on both colour (table 22) and black-and-white (table 20) prints differred significantly at the five percent level from ground-measured heights of the same trees. However when felled heights were compared with photo and standing heights (table 21) for the South Canol Road plots, the two were found to be equally accurate. The standard error of estimate of the photo to the standing heights was much poorer for the colour (table 23) than for the black-and-white prints (table 21).

5.4 Discussion

Tree height is the most important variable used with large-scale photo plots to predict volume. Measurements of such heights were done in this test with much more accuracy (and far less difficulty according to the photogrammetrist) on black-and-white than on colour twice-enlarged prints.

This test may have been unintentionally biased against the colour imagery. It was exposed on a bright sunny day in late August when, in such northern latitudes, tree shadows are long due to the low sun-angle. The black-and-white photographs, obtained two days earlier, were exposed under a heavy overcast where shadows were minimized and advantage could be taken of the wide exposure latitude of the film

Table 20. Randomized complete block anova[1] comparing ground- to photo[2]-measured tree heights made on black-and-white prints

Anova Table					
Source of Variation	df	SS	MS	F	Critical F
Measurement Method	1	14.59	14.59	21.32	3.84
Individual Trees	242	2,119.00	8.76	12.80	1.16
Remainder	242	165.58	0.68		
Total	485	2,299.17			

[1]Analysis of variance at 5% level of significance
[2]243 lodgepole pine heights measured on 6 plots on black-and-white twice-enlarged LSP prints S. Canol Road

Table 21. Statistical comparison of tree heights[1] measured on the ground and on[2] black-and-white prints

Measurement Method	Mean Height	Standard Deviation	Felled r^2	Felled SE E	Standing SE E
Photo	15.7000	1.94701	0.80165	0.97635	0.98619
Standing	15.3934	2.16871	0.79725	0.98713	
Felled	15.5698	2.18179			

[1]105 lodgepole pine heights from 3 LSP plots
[2]Heights were measured standing, felled and on twice-enlarged black-and-white prints

Table 22. Randomized complete block anova[1] comparing standing to photo-measured white spruce heights on colour prints[2]

Anova Table

Source of Variation	df	SS	MS	F	Critical F
Measurement Method	1	18.65	18.65	10.02	3.84
Individual Trees	634	12,904.67	20.35	10.94	1.00
Remainder	634	1,180.12	1.86		
Total	1,279	14,103.44			

[1]Analysis of variance 5% level of significance
[2]635 trees measured on twice-enlarged colour prints

Table 23. Statistical comparison of white spruce heights measured standing and on colour prints[1]

Measurement Method	Mean Height	Standard Deviation	Standing r^2	Standing SE E
Photo	9.4331	3.6396	0.71	1.62173
Standing	9.1881	3.0145		

[1]635 tree heights measured in 12 Braeburn plots

employed. The helicopter used to transport the camera system for the Braeburn Lake photography was a less stable photographic platform than the twin otter used for the South Canol Road operation (even though the latter machine had to fly through a rain squall to obtain the photography). Finally, the forest conditions (species, tree heights and topography) varied between the two test sites, although this difference was offset by the open character of the stands concerned (the photogrammetrist had no difficulty seeing the ground under either the pine or the spruce stands).

This test indicated that photo plots on black-and-white twice-enlarged prints could be used with confidence as a part of any Yukon forest inventory. The wider exposure latitude which made obtaining clear prints even in the midst of a storm possible would often be an asset in inventory operations. More tests with the colour prints would be desirable before that imagery is rejected for LSP applications in the Yukon.

6. Interpreter Effect

Usually if more than one photointerpreter or photogrammetrist is involved in a project, one of the project conclusions is that the interpreter or photogrammetrist has a significant impact on the results obtained. Lee (1959) and Smith *et al.* (1960) listed the "interpreter effect" as the most important source of variation in photo-mensuration. Smith (1957) also remarked that the variation within and between interpreters was one of the most influential factors affecting measurement accuracy. Most foresters utilizing photogrammetrists account for this human variability by calibrating each interpreter almost like one would calibrate any other piece of equipment before beginning a new project (Bradatch 1978, Kirby 1979, Aldred 1979).

6.1 Problem Outline

Most of the research into variations between photogrammetrists has involved medium-scale photography on which measurements were made using pocket stereoscopes. Are the results described in the literature valid for measurements on large-scale photos made by photogrammetrists using stereoscopes of superior quality?

6.2 Experimental Methods

6.2.1 Hypothesis and Tests

To test for differences between photogrammetrists the following hypothesis was constructed:

> There is no difference in the accuracy with which different photogrammetrists using the same equipment can measure tree heights on large-scale aerial photography.

This test involved the the measurement of tree heights in large-scale photo plots on the same Stereocord by three photogrammetrists. Their measurements were compared to ground-measured heights of the same trees using a one-way anova at the five percent level of significance.

6.2.2 Test Sites

The sites used in this test were the same ones described in detail in section 2.2.2 of this thesis.

6.2.3 Measurement Procedures

Three photogrammetrists using the same Stereocord measured the same 127 trees of 5 species on 12 photo plots placed on twice-enlarged prints of 1:1000 black-and-white aerial photography. The trees were then measured on the ground as described in section 2.2.3. The four sets of height measurements were then compared.

6.3 Results

Tables 24 and 25 show that no significant difference was found between the height estimations made by the photogrammetrists nor between the photo and ground height measurements of the same trees.

6.4 Discussion

The test results indicate that after calibration different photogrammetrists using a Stereocord can measure tree heights in a consistent fashion on large-scale aerial photographs. As tree height is the main factor used to estimate tree volume on LSP imagery, a forest inventory of the Yukon could be conducted using photo plots in lieu of ground plots with consistent results even if more than one photogrammetrist were employed during the course of the inventory.

Table 24. One-way anova[1] comparing felled and photo[2] tree heights measured by three interpreters versus felled heights

Anova Table					
Source of Variation	df	SS	MS	F	Critical F
Between Methods	3	19.0598	6.3533	0.69	3.12
Within Methods	504	12,347.2249	24.4985		
Total	507	12,366.2813			

[1]Analysis of variance at the 5% level of significance
[2]127 trees of 5 species in 12 plots in southwestern Alberta

Table 25. Statistical comparison of tree heights[1] estimated by three interpreters[2] versus ground measurements

Measurement Method		Mean Height	Standard Deviation	Standard Error
Felled		16.3119	4.8440	0.4298
Interpreter	1	16.3582	4.9707	0.4411
	2	16.4023	5.1242	0.4847
	3	15.9157	4.8543	0.4307

[1]127 trees of 5 species in 12 plots in southwestern Alberta
[2]Three used a Stereocord to measure tree heights on twice-enlarged black-and-white prints

7. Conclusions

The managers of the Yukon's forest resources require information concerning the resource distribution, quantity, quality and condition. Only through the introduction of a continuous inventory program can that information be provided. The funding of such a program is constrained by the limited value of the resource involved. This cost limitation makes the use of traditional approaches utilizing ground-measured plots hard to justify due to the high access costs inherent in northern operations. However, a survey based on the employment of large-scale photo plots has the potential of satisfying inventory cost limitations and the capability of fulfilling most of the informational needs of forest managers.

This thesis has answered a number of the questions which must be solved in the design of a Yukon inventory based on large-scale photo plots. The first test addressed the problem of hardware selection. The accuracy with which individual tree heights and plot areas could be measured using FMI and NFRC equipment was assessed. No significant differences were found between either method and ground measurements of the same variables, indicating that either LSP system could provide accurate tree heights and plot areas as a part of a Yukon forest inventory. Further study is suggested of the consequences of ignoring tilt during operational surveys based on LSP techniques, but only after forest managers have defined what standards of accuracy are

acceptable in forest inventories and the extent to which funding will be made available to attain those standards.

Within the Canadian Forestry Service two different regression equations have been developed for estimating individual tree volume on large-scale photo plots. The FMI equation utilizes tree height and crown area while the NFRC equation depends on tree height alone. A test of the two showed that individual tree volumes can be estimated accurately using either equation, neither yielding results significantly different from ground-measured values. This result means that in the Yukon plot measurements need not include tree crown area, reducing the time necessary to measure each photo plot by half. Since only one tree species (lodgepole pine) was included in this test, trials with other Yukon species should be made to confirm that this result was not affected by the tree species used in the test.

While Canadian researchers generally agree that for general inventory purposes an LSP film scale of 1:1000 is desirable, the scale and type of imagery used for actual plot measurements has not been standardized. The third test in this study involved a comparison of tree heights and plot areas measured on various types of black-and-white photographs to ground measurements of the same variables. Tree heights measured on contact prints were found to correlate most closely to felled heights, followed by heights measured on twice-enlarged prints and on negative transparencies.

However only plot areas measured on twice- and four-times-enlarged prints did not differ significantly from ground values. It was therefore concluded that a Yukon inventory based on large-scale aerial photo plots should use twice-enlarged prints as the plot measurement medium.

Thirdly, a comparison of tree height measurements made on twice-enlarged colour and black-and-white prints to the heights of the same trees standing was made. Measurements on the black-and-white prints approximated standing heights more closely than those made on the colour prints. Tree heights were measured as accurately on the black-and-white prints as on the ground on the standing trees (with a clinometer and chain). This result indicates that plots placed on such prints could be used during the course of a Yukon inventory with the expectation of achieving results comparable to those which could be expected from employing traditional ground plots.

Finally, a test made by three photogrammetrists using a Stereocord on twice-enlarged prints to measure tree heights showed that such measurements did not differ significantly from each other or from ground measurements of the same trees. This comparison illustrated that consistent results can be expected in a Yukon forest inventory which utilizes large-scale photo plots as its main sampling means even if more than one photogrammetrist is employed to measure the plot variables.

This study has explored many of the alternatives which must be weighed before a forest inventory utilizing large-scale aerial photo plots can be introduced into the Yukon. As a result of the various tests, it is recommended that a system incorporating the following features be implemented in the Territory:

1. utilization of the NFRC photo acquisition and measurement equipment due to its substantially lower acquisition cost,
2. estimation of tree volumes based on total tree height alone, and
3. use of black-and-white twice-enlarged prints as the primary photographic medium.

The introduction of such a program should provide forest managers with a reliable and efficient means of obtaining the data required for effective resource management.

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Appendix I: Selected Definitions[2]

Accuracy - the degree of conformity with a standard, or the degree of perfection attained in a measurement. Accuracy relates to the quality of a result, and is distinquished from precision, which relates to the quality of the operation by which the result is obtained.

Air base - the line joining two air stations, or the length of this line; also, the distance (at the scale of the stereoscopic model) between adjacent perspective centres as reconstructed in a plotting instrument.

Altimeter (radar) - an instrument, called a radar altimeter, used for determining an aircraft's height above terrain by the measurement of time intervals between the emissions and return of electromagnetic pulses.

Altitude (aerial photography) - vertical distance above the datum, usually mean sea level, of an object or a point in space above the earth's surface;

Attitude (photogrammetry) - the angular orientation of a camera, or of the photograph taken with that camera, with respect to some external reference system.

Calibration - the act or process of determining certain specific measurements in a camera or other instrument or device by comparison with a standard, for use in correcting or compensating errors for purposes of record.

Calibration correction - the value to be added to or subtracted from the reading of an instrument to obtain the correct reading.

Colour photography - photography in which either the direct-positive or the negative-positive colour process is used.

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[2]Source: Slama, C.C. (ed.) 1980. Manual of Photogrammetry. 4th ed. American Society of Photogrammetry. 1056 pp.

Conjugate principal point or corresponding principal point the principal point of one aerial photograph where it appears on the adjacent overlapping area of the stereopair of photos (assuming more than 50% overlap).

Contrast (photography) - the actual difference in density between the highlights and the shadows on a negative or positive.

Correlation (general) - the statistical interdependence between two quantities.

Emulsion (photography) - a suspension of a light-sensitive silver salt (especially silver chloride or silver bromide) in a colloidal medium (usually gelatin), which is used for coating photographic films, plates and papers.

Enlargement - the production of a negative, diapositive or print at a scale larger than the original.

Exposure - the total quantity of light received per unit area on a sensitized plate or film.

Film - a plastic base which is coated with a light sensitive emulsion for use in a camera or printing frame.

Image - the permanent record of the likeness of any natural or manmade feature, objects or activities. Images can be acquired directly on photographic materials using cameras.

Imagery - the visual representation of energy recorded by cameras and other remote sensing instruments.

Infrared film - film containing an emulsion sensitive to infrared and blue light.

Intervelometer - a timing device for automatically operating the shutter of a camera at selected intervals.

Latitude - the range of photographic exposure which will result in a satisfactory negative.

Negative - a photographic image on film, plate or paper, in which the subject tones to which the emulsion is sensitive are reversed or complimentary.

Parallax - the apparent displacement of the position of a body, with respect to a reference point or system, caused by a shift in the point of observation. Parallax difference - the difference in the absolute stereoscopic parallaxes of two points imaged on a pair of photographs.

Photogrammetry - the art, science and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and phenomena.

Photograph - a general term for a positive or negative picture made with a camera on sensitized material, or prints from such a camera original.

Photointerpretation or photographic interpretation - the detection, identification, description and assessment of the significance of objects and patterns imaged on a photograph. Air photo interpretation or aerial photographic interpretation - photointerpretation applied to images on aerial photographs or to other aerial remote sensing imagery.

Positive - (1) a photographic image having approximately the same rendition of light and shade as the original subject (2) a film, plate or paper containing such an image.

Print (photography) - a copy made from a transparency by photographic means. Contact print - a print made with a transparency in contact with the sensitized surface.

Principal point (photogrammetry) - the foot of the perpendicular from the interior perspective center to the plane of the photograph.

Remote sensing - in the broadest sense, the measurement or acquisition of information of some property of an object or phenomenon, by a recording device which is not in physical or intimate contact with the object or

phenomenon under study.

Remote sensing imagery - the photographic and electronic image secured from platforms such as aircraft and satellites.

Resolution - the minimum distance between two adjacent features, or the minimum size of a feature, which can be detected by remote sensing.

Scale - the ratio of a distance on a photograph or map to its corresponding distance on the ground.

Speed (film, camera or paper) - the response or sensitivity of the material to light, often expressed numerically according to one of several systems (e.g. DIN and ASA exposure index).

Stereoscopic pair (photogrammetry) - two photographs of the same area taken from different camera stations so as to afford stereoscopic vision; frequently called a stereopair.

Sun-angle - elevation of the sun above the apparent horizon, usually measured in degrees. It is a critical parameter in aerial photography since sun-angle affects shadows.

Tilt - the angle at the perspective centre between the photograph perpendicular and the plumline (or other exterior reference direction); also, the dihedral angle between the plane of the photograph and the horizontal plane.

Transparency - a photographic print on a clear base, especially adapted to viewing by transmitted light.

Appendix II: Linear Regression for LSP Tree Heights

No.	Tree Heights Standing	Felled	Tree Species	No.	Tree Heights Standing	Felled	Tree Species
1	24.0	24.8	Aspen	17	13.5	13.8	Poplar
2	24.9	24.8	"	18	18.1	17.4	"
3	24.9	24.8	"	19	13.8	14.2	"
4	24.5	24.5	"	20	15.4	14.5	"
5	22.5	22.3	"	21	14.0	14.5	"
6	25.4	24.5	Poplar	22	14.6	14.5	"
7	26.2	26.3	"	23	15.9	15.5	"
8	25.6	26.2	"	24	13.7	13.5	"
9	21.5	22.3	"	25	14.1	14.3	"
10	22.8	22.8	"	26	15.7	15.8	"
11	24.5	23.8	"	27	16.3	15.0	"
12	12.7	12.7	"	28	15.6	14.6	"
13	20.4	18.5	"	29	26.0	25.1	L.Pine
14	13.5	13.6	"	30	24.0	23.7	"
15	11.7	12.0	"	31	25.6	25.1	"
16	13.5	14.0	"				

Model: $y = a + bx$

where y is the estimated value of 'felled height'
x is the independent variable 'standing height'
a = 0.1339878758
b = 0.9837727095
with r^2 = 0.98519